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To Pat, with love

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Studies in Medieval
Islamic Technology

From Philo to al-Jazarī –
from Alexandria to Diyār Bakr

edited by
David A. King

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This volume contains xxvi + 368 pages

PUBLISHER'S NOTE

The articles in this volume, as in all others in the Collected Studies Series, have not been given a new, continuous pagination. In order to avoid confusion, and to facilitate their use where these same studies have been referred to elsewhere, the original pagination has been maintained wherever possible.

Each article has been given a Roman numeral in order of appearance, as listed in the Contents. This number is repeated on each page and quoted in the index entries.

EDITORIAL PREFACE

The scholarly world knows of the major publications of Donald Hill: his books on al-Jazarī and the Banū Mūsā, his little book on water-clocks; his overview of Islamic engineering (with A. Y. al-Hassan); and his useful little history of engineering in classical and medieval times. The purpose of this volume is two-fold: first to pay tribute to the man and his contributions to scholarship, and second to gather the most significant of his various articles that are scattered in various journals and collected works.

To achieve that first aim I include below a personal tribute to Donald, modified from my notice about him which appeared in the journal *Arabic Science and Philosophy* in 1995, and supplemented by information from the eloquent obituary that appeared in *The Times* of London on 27 June, 1994. The author of that obituary was Anthony Turner, who graciously consented to my using it and then polished the final version which appears below. I append a list of Donald's publications.

The achievement of the second aim is very much due to John Smedley, editor of *Variorum*, who sent me occasional faxes to remind me that I promised him to prepare this volume in 1994. It was the awesome prospect of preparing the indexes which kept me waiting until October, 1997, when finally I had a whole week free to devote to the task. The delay at least ensured that paper X was included here.

To what is recorded in the notice that follows I can only add that it was for me a pleasure to know Donald Hill from 1973, when we met in Aleppo, to my last visit to him in his home in Great Bookham in 1989. It was always comforting to know that there was Donald Hill working away on Arabic texts on mechanical devices, and

he clearly drew some comfort from the fact that Ted Kennedy was working away at Arabic astronomical texts, with four of his students, Richard Lorch, Julio Samsó, George Saliba, and myself doing our best to pick up where Kennedy left off. And such texts on mechanical devices were all for Donald. So, for example, when I stumbled across a manuscript of an Andalusian treatise on mechanical devices in the Biblioteca Laurenziana in Florence in 1974, the sensible thing to do was to alert Donald of its existence, whereupon he published a preliminary account of it (XVII).¹ His attribution of the treatise to Abū ‘Abdallāh Ibn Mu‘ādh al-Jayyānī is unfortunately incorrect, as he was soon to realize: the author is Ibn Khalaf al-Murādī, otherwise unknown to us. Likewise when I found a previously-unrecorded manuscript of the treatise on mechanical devices by the Banū Mūsā in the Topkapı Library in 1975, with better diagrams than those in other available manuscripts, I alerted Donald and he, with mixed feelings, had to redraw all of the diagrams for his book on the treatise.² It was a particular pleasure for me to be able to help Donald in this limited way. Alas he never consulted with me or any of my colleagues when he was writing on Islamic astronomy and mathematics. As a result, there are a few errors in his writings on those subjects, not committed by him, but simply well-established in the literature that he was citing.³ When we met for the last time in 1989 my wife and I were travelling by car with my father, from Buckinghamshire to Frankfurt; we stopped off in Great Bookham. It was a most interesting experience to witness the encounter of two men (my father was only seven years older than Donald) who had both in a sense, by sheer love of their subject, dedication, native wit and hard work, beaten the established academic system in England.

The choice of the articles was rather delicate, but I made a deliberate attempt to provide the reader with access to Donald’s early papers on trebuchets and camels and horses (XIX and XX) and his first writings on what he liked to call “fine technology” (I and II). Particularly important studies are his overview of the textual

sources for the history of Islamic technology (V) and his findings in the writings of medieval Muslim geographers (VI). There is a preview of the contents of the treatise of the Banū Mūsā (XII), but alas no similar overview of al-Jazarī's treatise for comparison: the reader must simply consult Donald's books. The newly-discovered Florence manuscript enabled Donald to present an overview (XVII) of a work which has completely changed our understanding of Andalusian technology and raised numerous questions that have still to be answered. His papers on mining and hydraulic technology (VII and VIII) show what an Arabist and friend of the Islamic world can do with diverse textual and archaeological sources. The reader should also consult Donald's chapter on Islamic technology published posthumously in the new *Encyclopedia of the History of Arabic Science* (publication B36).

The compilation of the indexes was an extremely delicate task. It is difficult enough to prepare indexes of one's own works, let alone those of a colleague. I took certain liberties, mostly in an attempt to keep down their length. (John Smedley has good reason not to trust me in this regard.) Particularly important research articles like V and VI are indexed as fully as seemed reasonable. Articles of a more general nature have been indexed with less thoroughness; thus for VII on mining I suppressed place-names, preferring to include the names of the materials mined. I have made a deliberate effort to cover technical terms and have put them in a separate index, in the hope that this might be of use to future researchers.⁴

Notes

- 1 Namely in item no. B4 in the bibliography that follows, reprinted here as no. XVII. I mentioned the treatise in a review of his book on al-Jazarī published as "Medieval Mechanical Devices", *History of Science* 13 (1975), pp. 284–289 (especially n. 8), repr. in my *Islamic Astronomical Instruments*, London: Variorum, 1987, repr. Aldershot: Variorum, 1995, XX. Scholarly reaction was immediate: see, for example, A. I.

- Sabra, "A Note on Codex Bibliotheca Medicea-Laurenziana Or. 152", *Journal for the History of Arabic Science* 1 (1977), pp. 276–283, and M. V. Villuendas, "A Further Note on a Mechanical Treatise Contained in Codex Medicea Laurenziana", *ibid.* 2 (1978), pp. 395–396. The subsequent literature on this very important manuscript is listed in Josep Casulleras, "El último capítulo del *Kitāb al-asrār fī natā'iy al-afkār*", in *idem* and Julio Samsó, eds, *From Baghdad to Barcelona. Studies in the Islamic Exact Sciences in Honour of Prof. Juan Vernet*, 2 vols, Barcelona: Instituto "Millás Vallicrosa" de Historia de la Ciencia Arabe, 1996, pp. 613–653, especially p. 613, n. 2. The reason for the mis-attribution to Ibn Mu'ādh is that the following treatise in the manuscript is indeed by Ibn Mu'ādh: on this see now M. V. Villuendas, *La trigonometría europea en el siglo XI - Estudio de la obra de Ibn Mu'ād: El Kitāb Maḥlāt*, Barcelona: Instituto de Historia de la Ciencia de la Real Academia de Buenas Letras, 1979, where, however, the treatise on mechanics is not mentioned.
- 2 Compare his article on the treatise of the Banū Mūsā listed in the bibliography as B5 and reprinted here as XII, p. 47, note, and Donald's book on the same subject listed as A4, pp. ix and 14–16.
 - 3 One error that should be mentioned is the attribution of the spherical cosine formula to al-Battānī (item B32 of the bibliography, pp. 490–491, and elsewhere) and the prosthapheretical formula to Ibn Yūnus (item A4, p. 29). Just because a medieval author used a procedure which is mathematically equivalent to a modern formula, this does not mean that he knew the formula. In fact al-Battānī did not use spherical trigonometry at all, and Ibn Yūnus proposed equivalent solutions to a problem of spherical astronomy which can be seen to be equivalent by virtue of the prosthapheretical formula. But such claims litter the modern literature and they will continue to be repeated.
 - 4 For technical terms in medieval technological treatises one should consult the copious indexes of Eilhard Wiedemann, *Aufsätze zur arabischen Wissenschaftsgeschichte*, 2 vols, Hildesheim & New York: Georg Olms, 1970; and *idem*, *Gesammelte Schriften zur arabisch-islamischen Wissenschaftsgeschichte*, 3 vols, Frankfurt am Main: Institut für Geschichte der Arabisch-Islamischen Wissenschaften, 1984–85. Donald's main glossary is to be found in his book on the treatise of the Banū Mūsā, pp. 253–265. There are also glossaries in the Arabic editions of the texts of the Banū Mūsā and al-Jazarī (see endnote 4 to the section that follows).

ACKNOWLEDGMENTS

John Smedley's usual tolerance, forbearance and patience were this time somewhat stretched, but his encouragement was incessant. Anthony Turner contributed suggestions, criticism and above all encouragement in the preparation and organization of this volume; this was but a small part of our continuous collaboration over many years. Kurt Maier (Frankfurt) typed the raw indexes from highlighted photocopies of the various articles. After I had organized the raw data into a preliminary version of the final indexes François Charette (Frankfurt) controlled various problematic entries and made numerous corrections and additions. He then prepared the camera-ready copy of the indexes, of the introductory sections and of five of the articles.

For permission to reprint the various articles I thank the following co-authors: Ahmad Yusuf al-Hassan (VII), Kamal Shehadeh (X) and Richard P. Lorch (X), and the following publishers: The American University of Beirut, Beirut, Lebanon (I); the Institute for the History of Arabic Science, Aleppo (II, XVI, XVII); the Société Internationale de l'Astrolabe, Paris (III); Ithaca Press, an imprint of Garnett Publishing, Reading (IV); Cambridge University Press (V); Mansell, an imprint of Cassell of London, for *History of Technology* (VI and XII); the editors of the *Encyclopaedia of Islam* at E. J. Brill, Leiden (VII, VIII, XI, XIII); Les Belles Lettres, Paris (IX); the Institut für Geschichte der Arabisch-Islamischen Wissenschaften, Frankfurt am Main (X); *Annals of Science* and Taylor & Francis, London (XIV); Simon & Schuster, New York, for Charles Scribner's Sons, formerly of New York (XV); Secretaría de Estado de Cultura, Madrid (XVIII); the Center for Medieval and Renaissance Studies, University of California, Los Angeles (XIX); and Oxford University Press (XX).

Donald Routledge Hill, 1922–1994*

“On my return (from seeing the superb miniatures of al-Jazarī in the Aya Sofya library) I kept telling my lamented colleague Gustave von Grünebaum that the engineering relations between Islam and the West could never be understood until al-Jazarī was edited; and he kept replying, ‘Who knows enough both of technology and of Arabic to do it?’.”
Lynn White, Jr., in his foreword to Donald Hill's book on al-Jazarī.

Donald was born in London on August 6, 1922. He served in the Middle East as a lieutenant in the Royal Engineers from 1941 to 1946, including two years in the Eighth Army in North Africa and Italy, where he was wounded in action. In 1949 he obtained a degree in engineering from London University and joined the Iraq Petroleum Company, for whom he worked on construction projects in the Lebanon, Syria and Qatar. In 1947 in Beirut he married Patricia Sulmen of Jerusalem. Back in England he held several senior posts in major petro-chemical companies from 1955 until his retirement in 1984.

Donald was a competent linguist. Having already mastered French, German, Spanish and Italian, his sojourn in the Middle East provided the opportunity to add colloquial Arabic to his list. But he also mastered the intricacies of classical Arabic, and ventured into

*Modified from the obituary notice in *Arabic Science and Philosophy* 5 (1995), pp. 297–302. That notice relied to some extent on the eloquent obituary in *The Times* (London), June 27, 1994, more of which has been inserted here. This writer is indebted to the author, Anthony Turner, for his generous permission to use it, as well as for his improvements to the penultimate version of the present notice.

the field of Islamic history. He received an M.Litt. degree in Islamic history from the University of Durham in 1964 and a Ph.D. from the University of London in 1970. His thesis was a comprehensive computer analysis of the termination of hostilities during the early phase of the Arab conquests.

Donald's early study of trebuchets arose out of his awareness of the inadequacy of the Arabs in siege warfare during that early period. This brought him into contact with Lynn White Jr. of the University of California, the leading historian of medieval technology. And it was Lynn White who drew Donald's attention to a medieval Arabic treatise on mechanical devices, known to the scholarly world only through a partial German translation by Eilhard Wiedemann and Fritz Hauser (1915). The subject of medieval Islamic technology had barely progressed since the time of Wiedemann, who died in 1928. By the time Donald published *The Book of Ingenious Mechanical Devices* by Ibn al-Razzāz al-Jazarī in 1974 he was recognized as the leading authority on the subject. For this book he was awarded the Dexter Prize of the American Society for the History of Technology in 1974 (jointly with Daniel Boorstin). But this was just the beginning. Of major importance to drawing attention to Donald's work was the fact that two years after his book was published, the realization of an exhibition "Science and Technology in Islam" in the context of the World of Islam Festival in London provided an opportunity to test the firmly held and stongly iterated opinion that all al-Jazarī's machines were totally impractical. For the exhibition held in the Science Museum in 1976, three of al-Jazarī's machines - a phlebotomy device, a double-acting pump and the "castle" water-clock - were reconstructed. All three were built without great difficulty following al-Jazarī's instructions and all three worked well. Particularly impressive was the mechanically-complex water-clock some four metres high and about 3 metres deep, in which all sorts of things happen at each hour. The reconstruction is described in Donald's book on water-clocks.¹ Some 20 years later the clock was exhib-

ited in Amsterdam.² In the same way as watching the norias turn at Hama gives an impression of the life of materials as the wood creaks, groans, shudders and sings, and one beholds the beauty of the water cascading in the sunlight from the overflowing containers, so the rebuilt castle-clock, all its mechanism hidden away, gives a sense of the wonderment such mechanical marvels must have evoked, leaving one to ponder on the nature of the spirits imprisoned within it. The medieval literary equation of mechanics with magic has been well documented. Hearing the castle water-clock and seeing its automatic activities, makes one realize that the literary trope reflects medieval reality.³

When justice had been done to al-Jazarī, Donald set about preparing for publication the translation and commentary of two earlier treatises, those of the Banū Mūsā and Pseudo-Archimedes, as well as a survey of Arabic treatises on water-clocks. He became interested in the social context of technological ideas and their transmission from one culture to another. Donald's collaboration over many years with Ahmad Yusuf al-Hassan on a history of Islamic technology took him far away from the Banū Mūsā and al-Jazarī. Also Dr. al-Hassan had the facilities in Aleppo to publish the edited texts of both al-Jazarī and the Banū Mūsā.⁴ I can claim some input in this monumental undertaking because I raised the question in my review of Donald's book on al-Jazarī: it is nice to have a new translation, more readable than anything of Wiedemann's, but where is the edited text, or at least a facsimile of the best available manuscript?⁵ In 1984 Donald published a *History of Engineering in Classical and Medieval Times*. And he did not shy away, as others of us did, from an invitation by Edinburgh University Press to prepare *Islamic Science and Technology*, alas his last major work.

Over the years Donald retained his affiliation with the School of Oriental and African Studies in London but essentially worked in isolation and without institutional backing. It was he who inspired others to publish the Arabic texts of the treatises of al-Jazarī and

Taqī 'l-Dīn. But it is most unfortunate that he had no students, and he does not seem to have a successor. His papers, which I had the privilege of inspecting in November, 1994, were (at least compared with my own) remarkably tidy and well-organized. This does explain how he was able to publish one book after the other.

Some days before his death on May 30, 1994, Donald signed and dispatched to various colleagues copies of his latest book, *Islamic Science and Technology*. Few scholars have the satisfaction of having devoted many years so fruitfully to a highly technical subject and also having produced a popular book in which the results of this research are made available to the educated public. Donald's little book will surely be for many years to come *the* book in the English language to which people will turn for a readable introduction to the many aspects of our field.

Donald was, in addition to his professional and academic achievements, very much a family man. His wife Pat, and later their three children and more recently their four grandchildren, were never far from his thoughts. The scholarly world shares their loss, for Donald ranks with B. Carra de Vaux, Eilhard Wiedemann and Lynn White among the main contributors to our understanding of medieval technology.

What is there left to do in this field now that Donald is no longer with us? A great deal. First, a colloquium "Aspects of Islamic Technology—in memoriam Donald Hill" was organized by the Society for the History of Medieval Technology and Science at the Warburg Institute, London, on April 1, 1995.⁶ Second, there is one topic that Donald was working on in his last years and for which his notes are available, alas not in the best of shape. I refer to wheels and perpetual motion as treated in various Arabic sources. I am looking for a competent young scholar of medieval Arabic with the necessary technical knowledge to complete Donald's study. Third, there is an Iranian tradition of fine technology which Donald left virtually untouched. There are treatises on fine technology

in Persian that have never been studied.⁷ And there is material in modern Iranian publications on the subject that needs to be incorporated into the corpus of literature that Donald built up.⁸ There is even material in modern Arabic publications that appears to have escaped Donald's notice.⁹ Fourth, the relevance of the Islamic textual material for the future of the archaeology of the Islamic world has to be taken seriously. There is, for example, still no properly-documented study of the water-operated astrolabic clock in Fez.¹⁰ The mathematics, and to some extent the technology behind such remarkable, truly Islamic, architectural features as the *muqarnas*, a honey-comb-type structure used from one end of the Islamic world to the other to decorate corners of ceilings and dome-foundations, is indeed described in texts.¹¹ Finally, there are close to a thousand medieval Islamic astronomical instruments, mainly in brass, that have never been seriously studied by a historian of technology. These precious sources are now to some extent under our control, firstly as far as their locations are concerned, and secondly as far as their inscriptions, dating, and provenance are concerned.¹² They have been studied so far only from the perspective of the history of astronomy, but they are also primary sources for the history of very fine technology.¹³

David A. King

Notes

- 1 *Arabic Water-Clocks* (listed as A5), pp. 103–111.
- 2 Catalogued in Anthony J. Turner, *Time*, The Hague: Tijd voor Tijd Foundation, 1990, pp. 72–73, no. 88.
- 3 These three sentences are in their essence taken from Anthony J. Turner, "Donald Hill and Arabic Water-Clocks", unpublished paper delivered at the 1995 London Colloquium (see n. 6 on p. xxii).
- 4 Ahmad Yusuf al-Hassan, ed., *Kitāb al-Hiyal* ("The Book of Ingenious Devices") by the *Banū Mūsā bin Shākir*, Aleppo: Institute for the History of Arabic Science, 1981;

- and *idem*, ed., *al-Jāmi' bain al-'ilm wal-'amal al-nāfi' fi šinā'at al-ḥiyāl* ("A Compendium on the Theory and Practice of the Mechanical Arts") by Ibn al-Razzāz al-Jazarī, Aleppo: Institute for the History of Arabic Science, 1979. See also *idem*, ed., *Taqī-al-Din and Arabic Mechanical Engineering, with The Sublime Methods of Spiritual Machines, An Arabic Manuscript of the Sixteenth Century*, Aleppo: Institute for the History of Arabic Science, 1976.
- We should also mention Muḥammad Aḥmad Dahmān, *'Ilm al-sā'āt wa-l-'amal biḥā ta'līf Riḍwān ibn Muḥammad al-Sā'ātī ... ma' majmū'a fi 'l-mikānik al-Islāmī* [= Riḍwān ibn Muḥammad al-Sā'ātī on the construction and use of clocks, with notes on Islamic mechanics], [Damascus]: Maktabat al-Dirāsāt al-Islāmiyya, n.d. [ca. 1980?].
- 5 But facsimiles have to be done properly. On the pitfalls see Jan-Just Witkam, "Arabic Manuscripts in Distress: The Frankfurt Facsimile Series", *Manuscripts of the Middle East* 4 (1989), pp. 175–180.
 - 6 The papers presented were the following: Emilie Savage-Smith, "Metallurgy, Magic and Divination"; Charles Burnett, "Islamic Technology and Magic"; Anthony Turner, "Donald Hill and Islamic Water-Clocks"; and Alan Williams, "The Metallurgy of Islamic Arms and Armour".
 - 7 See Storey, *Persian Literature - A Bibliographical Survey*, 5 vols, London: Luzac, 1927 onwards, II:3, section on mechanics on pp. 445–446.
 - 8 See Parviz Mohebbi, *Techniques et Ressources en Iran du 7e au 19e siècle* (Bibliothèque Iranienne, 46), Tehran: Institut Français de Recherche en Iran, 1996.
 - 9 Notably Muḥammad Aḥmad Dahmān's edition of Riḍwān al-Sā'ātī's treatise *'Ilm al-sā'āt wa-l-'amal biḥā*, Damascus, n.d. [ca. 1980].
 - 10 The best description is still Derek J. de Solla Price, "Mechanical Water Clocks of the Fourteenth Century in Fez, Morocco", *Proceedings of the Tenth International Congress of History of Science*, Ithaca, N.Y., 1962, pp. 599–602.
 - 11 Articles "Mukarbas" by A. Fernandez-Puertas and "Muḥarnas" by Doris Behrens-Abouseif in *El*², VII, pp. 500–501 and 501–506. For the most recent account of the technical literature see Yvonne Dold-Samplonius, "Practical Arabic Mathematics: Measuring the Muḥarnas by al-Kāshī", *Centaurus* 45 (1992), pp. 193–242.
 - 12 A long-awaited, but still unpublished, survey of Muslim instrument-makers, unfortunately listed alphabetically rather than organized in any historical or geographical manner, is Alain Brioux and Francis R. Maddison, *Répertoire des facteurs d'astrolabes et de leurs œuvres*, Paris: C.N.R.S. A catalogue of all medieval Islamic and European instruments, arranged chronologically by region, is described in D. A. King, "Medieval Astronomical Instruments - A Catalogue in Preparation", *Bulletin of the Scientific Instrument Society* (London), no. 31 (1991), pp. 3–7. This catalogue is not about to be published in the near future, but descriptions are already available for most Islamic and European instruments from before ca. 1550. On the kind of surprises that reward such detailed studies of instruments see *idem*, "Astronomical Instruments between East and West", in Harry Kühnel, ed., *Kommunikation zwischen Orient und Okzident*, Vienna: Österreichische Akademie der Wissenschaften, 1994, pp. 143–198.

- 13 Donald wrote (no. B31, reprinted as XVIII — see there p. 11 and n.6 on p. 16) that astronomical instruments belong “more properly to the history of astronomy rather than that of technology”. There I would say he erred. He modified his opinion when working on the geared luni-solar mechanism of al-Bīrūnī (no. B16), and in his latest books (nos A6 and A8) he devoted several pages to instruments. Metallurgical considerations, construction techniques, brazing and welding, screws, precision markings and scale-graduations, engraving and inlaying techniques. These are aspects of instruments which could teach us a great deal.

Useful studies of technological aspects of European instruments are to be found in Robert B. Gordon, “Metallography of Brass Made in the Sixteenth Century”, *Journal of the Historical Metallurgy Society* (London) (1986), pp. 93–96, and *idem*, “Sixteenth-Century Metalworking Technology used in the Manufacture of two German Astrolabes”, *Annals of Science* 44 (1987), pp. 71–84; and Allan Chapman, *Dividing the Circle: the Development of Critical Angular Measurement in Astronomy, 1500–1800*, London, 1990, and New York, 1990, 2nd edn, New York, Wiley & Sons, 1996; *idem*, “The Design and Accuracy of Some Observatory Instruments of the Seventeenth-Century”, *Annals of Science* 40 (1983), pp. 457–471; *idem*, “A Study of the Accuracy of Scale Graduation on a Group of European Astrolabes”, *Annals of Science* 40 (1983), pp. 473–488.

Donald R. Hill - Publications

Note: Boldface Roman numerals to the right of the entries refer to the reprints in this volume. The following abbreviations are used:

Al-Abhath: Journal published by the American University of Beirut.

DSB: *Dictionary of Scientific Biography*, 16 vols, New York: Charles Scribner's Sons, 1970–80.

*EI*²: *Encyclopaedia of Islam*, new edition, 8 vols to date. Leiden: E. J. Brill, 1960 to present.

IHAS: Institute for the History of Arabic Science, Aleppo.

JHAS: *Journal for the History of Arabic Science*, Aleppo: IHAS.

UR: Journal published by the Iraqi Cultural Centre, London.

A. Books

- 1 *The Termination of Hostilities in the Early Arab Conquests*, London: Luzac, 1971.
- 2 *The Book of Knowledge of Ingenious Mechanical Devices by Ibn al-Razzāz al-Jazarī*, Dordrecht (NL): Reidel, 1974, reprinted Islamabad: Pakistan Hijra Council, 1989.
- 3 *On the Construction of Water-clocks*, Occasional Paper No. 4, London: Turner & Devereux, 1976.
- 4 *The Book of Ingenious Devices by the Banū Mūsā ibn Shākir*, Dordrecht: Reidel, 1979, reprinted Islamabad: Pakistan Hijra Council, 1989. A Persian translation has been published in Mashhad, Iran, 1993.
- 5 *Arabic Water-Clocks*, (Sources and Studies in the History of Arabic-Islamic Science, History of Technology Series - 4), Aleppo: IHAS, 1981.

- 6 *A History of Engineering in Classical and Medieval Times*, London: Croom Helm, and La Salle, Ill.: Open Court, 1984, reprinted in paper-back, London and New York: Routledge, 1996. Divided into three parts as follows. I: Civil engineering: irrigation and water supply, dams, bridges, roads, building construction, surveying. II: Mechanical engineering: Water-raising machines, power from water and wind. III: Fine technology: Instruments, automata, clocks.
- 7 *Islamic Technology: An Illustrated History* (with Ahmad Y. Al-Hassan), Cambridge: Cambridge University Press and Paris: U.N.E.S.C.O., 1986. Contains chapters on: mechanical engineering; civil engineering; military technology; ships and navigation; chemical technology; textiles, paper and leather; agriculture and food technology; mining and metallurgy; engineers and artisans.
- 8 *Islamic Science and Engineering*, Edinburgh: Edinburgh University Press, 1993. Contains: Mathematics (arithmetic, algebra, geometry, trigonometry); Astronomy (folk astronomy, sources of Islamic astronomy, spherical astronomy, planetary theory, instruments, observatories, astrolagy); Physics (mechanics and optics); Chemistry (alchemy, industrial chemistry); Machines (water-raising machines, water-mill, wind-mills, siege engines); Fine Technology (Islamic sources, clocks, trick vessels, automata, fountains, miscellaneous); Bridges and Dams (bridges, dams); Irrigation and Water Supply (irrigation systems, measurement of irrigation waters, qanats, water-supply); Surveying (levelling, triangulation, quantity surveying); Mining (Islamic mines, maining techology, non-ferrous metallurgy, iron and steel metallurgy); Transmission of Islamic Knowledge to Europe (science, engineering).

B. Articles, chapters in books

- 1 “Trebuchets”, *Viator - Journal of the Center for Medieval and Renaissance Studies* (University of California, Los Angeles) 4 (1973), pp. 99–114. **XIX**
- 2 “The Camel and the Horse and the Early Arab Conquests”, in V. J. Parry and M. E. Yapp, eds, *War, Technology and Society in the Middle East*, Oxford: Oxford University Press, 1975, pp. 32–43. **XX**
- 3 “Mechanical Technology” in John R. Haynes, ed., *The Genius of Arab Civilization: Source of Renaissance*, 1st edn, New York: New York University Press, 1975 / Phaidon Press, 1976, pp. 175–187; 2nd edn, Cambridge, Mass.: MIT Press / Eurabia Ltd., 1983, pp. 203–215; Arabic edn, Cambridge, Mass.: MIT Press, 1978, pp. 187–199.
- 4 “A Treatise on Machines by Ibn Mu‘ādh Abū ‘Abdallāh al-Jayyānī”, *JHAS* 1 (1976), pp. 33–44. **XVII**
- 5 “The Banū Mūsā and their Book of Ingenious Devices”, *History of Technology* 2 (1977), pp. 39–76. **XII**
- 6 “Al-Jazarī”, *DSB*, vol. XV, suppl. 1 (1978), pp. 253–255. **XV**
- 7 “Notice of an Important al-Jazarī Manuscript”, *JHAS* 2, (1978), pp. 291–298. **XVI**
- 8 “Medieval Arabic Mechanical Technology”, *Proceedings of the First International Symposium for the History of Arabic Science*, Aleppo, April 5–12, 1976, Aleppo: IHAS, 1976 (published 1979), pp. 221–237. **II**
- 9 “Water-clocks”, in Alan Smith, ed., *The Country Life International Dictionary of Clocks*, New York: Putnam, 1979, pp. 129–135.
- 10 “Al-Djazarī”, *EI*², Supplement, fasc. 5–6 (1982), pp. 266–267.
- 11 “Ḥiyāl” [= Automata], *EI*², Supplement, fasc. 5–6 (1982), pp. 371–374.

- 12 “Traditional Islamic Engineering”, *UR* 1 (1982), pp. 37–39.
- 13 “Traditional Islamic Technology: Water Power”, *UR* 2/3 (1982), pp. 89–92.
- 14 “Traditional Mesopotamian Irrigation”, abridged translation of “Techniques hydrauliques en Mésopotamie ancienne” by R. van Laere, *Orientalia Lovaniensis Periodica*, University of Leuven Press, 1980, pp. 11–53, in *UR* 2 (1984).
- 15 “Information on Engineering in the Works of Muslim Geographers”, *History of Technology* 9 (1984), pp. 127–142. **VI**
- 16 “Al-Bīrūnī’s Mechanical Calendar”, *Annals of Science* 42 (1985), pp. 139–163, repr. in J. V. Field, D. R. Hill and M. T. Wright, eds, *Byzantine and Arabic Mathematical Gearing*, London: Science Museum, 1985. **XIV**
- 17 “Ḳuṣṭā b. Lūḳā”, *EI*², vol. V (1986), pp. 529–530. **XIII**
- 18 “Hydraulic Machines” (Section 3 of the article “Mā” [= Water]), *EI*², vol. V (1986), pp. 860–862. **VIII**
- 19 “Mining Technology” (with A. Y. Al-Hassan), (Section 2 of the article “Ma’din” [= Mines]), *EI*², vol. V (1986), pp. 967–973. **VII**
- 20 “Engineering in the Medieval Arab World”, *Arab Affairs* 2 (Winter 1986/7), pp. 38–46.
- 21 “Islamic Fine Technology and its Influence on the Development of European Horology”, *Al-Abhath* (Beirut) 35 (1987), pp. 9–28. **I**
- 22 “Engineering”, in *Cambridge History of the Middle East*, Cambridge: Cambridge University Press, 1988, pp. 269–270.
- 23 Introduction to *Héron d’Alexandrie: Les Mécaniques ou L’Élévateur des corps lourds*; facsimile of the 1984 edn by Bernard Carra de Vaux, Paris: Les Belles Lettres, 1988, pp. 9–20. **IX**
- 24 “I precedenti greci dell’ingegneria europea del Medioevo”, in *Ars et Ratio dalla torre di Babele al ponte di Rialto*, Palermo:

- Sellerio, 1990, pp. 225–244.
- 25 “Miḳyās” [= the Nilometer], *EI*², vol. VII (1990), pp. 39–40. **XI**
- 26 “Mathematics and Applied Science”, chapter 14 of M. J. L. Young, J. D. Latham and R. B. Serjeant, eds, *Religion, Learning and Science in the Abbasid Period*, (Cambridge History of Arabic Literature), Cambridge: Cambridge University Press, 1990, pp. 248–273.
- 27 “The Literature of Arabic Alchemy”, *ibid.*, chapter 18, pp. 328–341.
- 28 “Mandjanīk” [= Trebuchets], in *EI*², vol. VI (1991), pp. 405–406.
- 29 “Mechanical Engineering in the Medieval Near East”, *Scientific American* 264:5 (May 1991), pp. 100–105.
- 30 “Arabic Mechanical Engineering: Survey of the Historical Sources”, *Arabic Sciences and Philosophy* 1 (1991), pp. 167–186. **V**
- 31 “Tecnología andalusí”, in Julio Samsó et al., eds, *El legado científico andalusí*, Madrid: Ministerio de Cultura, 1992, pp. 157–172 and 298–309. **XVIII**
- 32 “Science and Technology in Ninth-Century Baghdad”, in P. L. Butzer and D. Lohrmann, eds, *Science in Western and Eastern Civilization in Carolingian Times*, Basel: Birkhäuser, 1993, pp. 485–502.
- 33 “Arabic Fine Technology and its Influence on European Mechanical Engineering”, in D. A. Agius and R. Hitchcock, eds, *The Arab Influence in Medieval Europe*, Reading: Ithaca, 1994, pp. 25–43. **IV**
- 34 “From Philo to al-Jazarī”, in W. D. Hackmann and A. J. Turner, eds, *Learning, Language and Invention: Essays Presented to Francis Maddison*, Aldershot: Variorum and Paris: Société Internationale de l’Astrolabe, 1994, pp. 188–206. **III**

- 35 “Construction of a Fluting Machine by Apollonius the Carpenter” (with Kamal Shehadeh and Richard P. Lorch), *Zeitschrift für Geschichte der Arabisch-Islamischen Wissenschaften* (Frankfurt am Main) 9 (1994/95), pp. 326–356. X
- 36 “Engineering”, in Roshdi Rashed and Régis Morelon, eds, *Encyclopedia of the History of Arabic Science*, 3 vols, London and New York: Routledge, 1996, vol. 3, pp. 751–795, with French translation “Technologie”, in *idem*, eds, *Histoire des sciences arabes*, 3 vols, Paris: Éditions du Seuil, 1997, vol. 3, pp. 11–54.

C. Reviews

- 1 Thorkild Schiøler, *Roman and Islamic Water-Lifting Wheels*, Odense (DK): Odense University Press, 1973; in *Technology and Culture* 15 (1974), pp. 628–630.
- 2 Seyyed Hossein Nasr, *Islamic Science: An Illustrated Study*, London: World of Islam Publishing Company Ltd., 1976, in *The Times Literary Supplement*, 30 April, 1976.
- 3 Ahmad Yusuf al-Hassan, *Taqī al-Dīn and Arabic Mechanical Engineering*, Aleppo: University of Aleppo Press, 1976, in *ISIS* 69 (1978), pp. 117–118.
- 4 Charles Singer et al., eds, *A History of Technology*, vol. VIII, Consolidated Indexes, compiled by Richard Raper, in *The Times Literary Supplement*, March 1985, p. 366.
- 5 Atilla Bir, *The Book “Kitāb al-Ḥiyāl” of Banū Mūsā bin Shākir: Interpreted in Sense of Modern System and Control Engineering*, Istanbul: Research Center for Islamic History, Art, and Culture, 1990, in *ISIS* 83 (1992), p. 480.

ISLAMIC FINE TECHNOLOGY AND ITS INFLUENCE ON THE DEVELOPMENT OF EUROPEAN HOROLOGY

It is generally accepted that the invention of the mechanical clock is one of the most important events in the history of technology. It was the first machine to use a steady gravitational pull as its motive force, and the means of controlling and transmitting that force embodied principles that were to be of great significance in the development of machine design. It is all the more unfortunate, therefore, that the ancestry of the mechanical clock has been largely neglected by western historians of technology and horology. One of the few scholars to attempt to make up for this neglect was the late lamented Derek de Solla Price and his comments on the subject are worthy of attention:

Now, the history of the mechanical clock is as peculiar as it is fundamental. Almost any book on the history of time measurement opens with a pious first chapter dealing with sundials and water clocks, followed by a chapter in which the first mechanical clock described looks recognizably modern. The beginning is indeed so abrupt that it often seems to me that the phrase "history of time measurement" must have been expressly coined to conceal from the public the awful fact that the clock (as distinct from other time-telling devices) had no early history. It appears to spring forward at birth fully formed and in healthy maturity, needing only a few improvements such as the substitution of a pendulum for the foliot balance and the refinement of the tick-tocking escapement into a precision mechanism.¹

The mechanical clock does, of course, have an early history and no-one has done more than Professor Price in tracing its origins; a little later we shall meet one of the devices which he identified as being among its ancestors. Although he acknowledged the Islamic contribution to the history of time-measurement, however, his researches were mainly directed elsewhere. Indeed, only in quite recent times has some of the important material in Arabic become easily

1 Derek de Solla Price, *Science since Babylon* (Yale University Press, 1975), p. 30.

accessible. My purpose in this paper is to attempt to trace the origins, development and diffusion of the various ideas and components which eventually coalesced into the mechanical clock. It should be borne in mind, however, that almost all these separate parts have identities of their own, either as parts of other machines or as machines in their own right.

The essentials of the mechanical clock in its early form were the weight-drive, the 'going train' of gears and the verge-and-foliot escapement. Some form of marking the passage of the hours was also necessary: the tower clocks of medieval Europe, in addition to dials, usually incorporated elaborate biological and celestial automata; the mechanism for striking the hours was activated by the 'striking train' of gears, which included segmental wheels, i.e. cogwheels having teeth on only part of their perimeters. If we examine some of the significant developments in fine technology, particularly in Islam, before the fourteenth century we shall be able to see how almost all this array of mechanisms came to be available when it was needed by the clockmakers.

It is not possible in the space available to enter into a detailed discussion about the origins of fine technology — the kind of engineering that is concerned with delicate mechanisms and sophisticated controls. It is known that mechanical devices were constructed in India as early as the third century B.C. and that elaborate timepieces incorporating biological automata were in use there in the eleventh century A.D.² In China, inflow clepsydras were in widespread use for timekeeping from about 200 B.C. onwards, and steelyard clepsydras are first mentioned in a Chinese book of A.D. 450, with the implication that they had been in use for some time before this date. The great water-clock described by Su Sung in a book completed in A.D. 1090 was probably derived from this relatively simple type of clepsydra. This was a monumental clock, driven by a scoop-wheel; the wheel was provided with a very ingenious escapement system, in essence two steelyards upon each of which the scoops acted in turn. When a scoop was full, its weight overcame the balancing system, and it fell freely for a given distance until checked, without recoil, by a locking device. The next scoop then came under the delivery jet and the cycle repeated itself. The clock was about 40 feet in height and included a rotating armillary sphere, together with numerous jackwork figures with both audible and visible effects.³

There is no evidence that Chinese or Indian ideas were transmitted westwards, and indeed the chronology would seem to preclude this possibility. For about 250 B.C., in the Fertile Crescent and Eastern Mediterranean, a tradition of fine technology was founded that flourished and grew from that time onwards. This

2 V. Ragavan, "Yantras or Mechanical Contrivances in Ancient India," *The Indian Institute of Culture* (Bangalore, 1952), Transaction No. 10.

3 Joseph Needham, *Science and Civilisation in China* (Cambridge, Cambridge University Press, 1965), vol. 4, pt. 2, pp. 446-66.

tradition, founded by Greeks, Egyptians and Syrians, was continued by their successors and descendants in the world of Islam, and later became a fertile source of inspiration to the peoples of other cultures.

Our earliest information about the origins of fine technology occurs in the writings of Vitruvius, who attributes the invention of the organ and the complex water-clock to an Egyptian engineer called Ctesibius. In Chapter 8 (vol 2, book 9) of *De Architectura*, Vitruvius describes two clocks constructed by Ctesibius, both which were operated by the steady rise of a float in the receiver of an inflow clepsydra. In one of these clocks there was a vertical rod soldered to the top of the float; the rod was toothed and meshed with a toothed drum. We are not told about the transmission mechanisms, although evidently there were other gears, but the end result was the activation of automata and the discharge of pellets. In the same chapter Vitruvius describes another clock, not attributed to Ctesibius, in which a chain attached to the float is passed round a horizontal axle. Fixed to the axle is a disc upon which a star map is engraved together with a Zodiac circle in which a small image of the sun can be set to its correct position for the day in question. An hour scale consisting of a network of bronze wires is placed close to the disc. As the disc rotates the 'sun' moves in a circular arc through the unequal hours for that day.⁴ The fragment of a plate from a clock of this type, dated to about the second century A.D., was discovered near Salzburg, evidence that this device continued in use in the Roman Empire.⁵

Another remarkable product of the so-called Hellenistic Age is the geared calendar known as the Antikythera Mechanism because of its discovery as part of the cargo of a sunken vessel in 1900 near the island of Antikythera (between Crete and Kythera). It was probably made in Rhodes about 87 B.C. It consists of a large number of gear wheels, all of which were turned by hand by the rotation of a single gear wheel. Among its purposes were the finding of the positions of the sun and moon, and the risings and settings of the circuit of notable fixed stars through the cycle of years and months. A very interesting part of the mechanism is a differential turntable, the purpose of which may have been to produce as output a function of the Metonic cycle of the moon.⁶

Treatises by two important writers have survived from the Hellenistic period. The *Pneumatics* of Philo (fl.c. 230 B.C.) exists only in a number of Arabic versions, all of which contain Islamic additions to Philo's original text. It is likely, for example, that several of the water-raising machines are of Islamic origin. Nevertheless, a number of machines can be positively attributed to Philo, and

4 Vitruvius, *De Architectura*, ed. F. Granger, 2 vols. (London: Loeb Classics, 1970) vol. 2, pp. 255-67.

5 H. Diels, *Antike Technik* (Leipzig and Berlin, 1914) pp. 213 ff.

6 Derek de Solla Price, *Gears from the Greeks* (New York: Science History Publications, 1975), *passim*.

indicate that he had a good grasp of the principles of pneumatics.⁷ From Hero of Alexandria (fl.c. 62 A.D.) we have the *Pneumatics* and the *Mechanics*, the latter extant in a good Arabic version by Qusṭā b. Lūqā, made in Baghdad towards the close of the 3rd/9th century.⁸ The *Pneumatics* is clearly derived from Philo's work, which it extends and amplifies. The *Mechanics* demonstrates a mastery of theoretical mechanics, and includes discussions on mechanical advantage and the use of complex gear-trains for moving heavy loads, although it is unlikely that these were ever incorporated in practical machines.

Another treatise, *On the Construction of Water-clocks*, carries the name of Archimedes (c. 250 B.C.), and this too exists only in Arabic versions.⁹ The water-clock was driven by the descent of a heavy float in a cylindrical reservoir, the speed of descent being kept constant by a feed-back control system: water from the reservoir discharged through a conical valve, the plug of which was soldered to the top of a small float in a float-chamber, which had an outlet pipe at the bottom. When water issued from this outlet the valve opened momentarily, water ran into the float-chamber from the reservoir and the valve closed momentarily — and so on. By this means an almost constant head was maintained in the float-chamber, and this ensured that the rate of discharge was also constant. Power from the float was transferred to a ball-release device through a pair of gears. The treatise describes a number of other automata, some of which may have been added by Philo, while others were certainly Arabic additions. Arabic writers are unanimous in attributing the invention of the feed-back control system and the ball-release mechanism to Archimedes and there is no reason to doubt this attribution, since Arabic engineers were usually very scrupulous in acknowledging their sources.¹⁰

We know that the tradition for building monumental water-clocks, with their associated automata, continued into Byzantine times and beyond. A clock of this type in Gaza was described by Procopius in the sixth century: there was a Gorgon, whose eyes rolled fearsomely at the end of each hour, and two rows of twelve doors each. The upper row was for the night, one being illuminated each hour by a light which moved at constant speed in front of the doors. The lower row was for the daytime; each door had two leaves. At the end of the first hour an eagle above the

7 Philo of Byzantium, "Le Livre des Appareils Pneumatiques et des Machines Hydrauliques par Philon de Byzance," Arabic text ed. with French translation by Carra de Vaux, *Paris Académie des Inscriptions et Belles Lettres*, 38 (1903), pt. 1.

8 *Pneumatics*, 1st ed. B. Woodcroft (London, 1851); facsimile of Woodcroft, ed. with introduction by Marie Boas Hall (London and New York: MacDonald, 1971); *Mechanics*, ed. with French trans. by Carra de Vaux, "Les Mécaniques ou l'Élevateur de Héron d'Alexandrie sur la version de Qusṭā ibn Lūqā," *Journal Asiatique*, ninth series, 1 (1893), pp. 386-472; 2, pp. 152-269, 450-514.

9 Donald R. Hill, *On the Construction of Water-clocks* (Occasional Paper no. 4, Turner and Devereux, London, 1976).

10 For example, al-Jazarī acknowledged his derivation of the water machinery in his first clock from 'Archimedes' and also makes respectful mention of the Banū Mūsā's work on machines.

first door unfolded its wings and moved forward. The door opened, while a figure of Helios, moving along a ledge in front of the doors, pointed to it. The figure of Hercules emerged from the door carrying the spoils of his first labour, the lion's skin, and the eagle covered his head with a victor's wreath. The hero then moved back into his niche and the door leaves closed upon him. A similar action occurred every hour, Hercules carrying in succession the spoils of his twelve labours. The hours were also marked by the activation of other automata and by the sounding of a gong. Unfortunately, Procopius tells us nothing at all about the machinery used to drive the clock and activate the automata.¹¹ Writing in 600/1203, Riḍwān b. al-Sa'atī tells us that the basic water-machinery of Archimedes was transmitted to Persia, where the feed-back control system was retained, whereas the other arrangements were changed and doors for the day and the night were added. This design was transmitted to Damascus in the days of the Byzantines and continued to be constructed in Umayyad times.¹² The description of the Gaza clock is a confirmation of Riḍwān's statement.

It should always be borne in mind, when discussing fine technology, that some of its ideas came from everyday machines. Of these the saqiya, the noria and the geared water mill are most relevant to our theme. The saqiya, a chain-of-pots driven through a pair of gears by an animal moving in a circle, was almost certainly invented in Egypt in the third century B.C.¹³ The noria, the compartmented water-driven wheel, probably originated in Syria or al-Jazīra, about 200 B.C.¹⁴ The question of the origin of the water mill driven by a vertical paddle-wheel through a pair of gears remains unresolved. Since Vitruvius implies, however, that it was invented by analogy with the noria, it may well be that its invention occurred in the same area some years later.

There is strong evidence in the foregoing summary, and from other material, to suggest that the main centre for the inventions of fine technology and utilitarian machines lay in Alexandria from about 300 B.C. to 300 A.D., although new ideas also saw the light in Greece, Asia Minor, Syria and Iran. In any case, although the language of culture in Seleucid Syria and Ptolemaic Egypt was Greek, the engineers themselves came from all the countries of the Middle East and the Eastern Mediterranean. Although the stream of invention lost much of its force in the four ensuing centuries, the tradition of fine technology and mechanical engineering remained intact until the advent of Islam.

The story of the establishment of Islam and the diffusion of the Arabic language

11 H. Diels, "Über die von Prokop beschriebene Kunstuhr von Gaza," *Abhandl. d. preuss. Akad. Wiss. Berlin* (Teubner: Phil. Hist. Klasse, 1917), No.7.

12 Donald R. Hill, *Arabic Water-clocks*, Institute for the History of Arabic Science, University of Aleppo, 1981, pp. 12-3.

13 Donald R. Hill, *A History of Engineering in Classical and Medieval Times* (London: Croom Helm, 1984), pp. 138-9.

14 *Ibid.*, 140-1.

from the Atlantic to Central Asia, in the two centuries following the Arab conquests, has been well documented. After the establishment of a homogeneous Islamic culture, the science and technology of earlier times were absorbed and then developed into recognisably Muslim forms. In some fields — irrigation for example — the process occurred very smoothly, simply because the indigenous engineers passed on their skills to their sons who were by then Arabic-speaking Muslims. Lack of space precludes detailed discussion of Muslim achievements in fields such as irrigation, milling and water raising, achievements that were the result of a combination of innovativeness and a large increase in the scale of operations. In undertakings of this kind, in which the machines and structures were durable, craftsmen could learn their professional skills on site, without recourse to written manuals. With fine technology things were rather different. We have seen that the art of constructing monumental water-clocks continued from Byzantine to Islamic times without interruption, and there may well have been existing water-clocks available for inspection. As in the case of heavy engineering, it is also probable that the skills of fine technology were passed on from master to pupil. It is certain, however, given the complexity of some of the smaller devices, that documents such as the treatises of ‘Archimedes’, Philo and Hero played an important role in transferring this technology into the world of Islam. Indeed, we know this to be so because, as already mentioned, Muslim engineers acknowledged such works as part of their inheritance.

Before proceeding to discuss the purely Muslim contributions to fine technology, it will be as well to recall the purpose of this paper, and to see which of the discrete elements of the mechanical clock were already present in the Muslim inheritance. In the saqiya and the water mill we have simple gears capable of transmitting high torque; in the Antikythera Mechanism we have complex gears, including a differential but *not* segmental or epicyclic gears. Neither in this device, nor in any other pre-Islamic examples, do we have the combination of complex gears and high torque. With reservations, because it is not freely suspended, the heavy float in the ‘Archimedes’ clock may be regarded as part of weight-drive, and the feed-back control system as a type of escapement. Biological automata were quite advanced and fairly simple celestial analogues had been introduced. Audible, as well as visual, signals were used for marking the passage of the hours.

The first substantial evidence for the development of fine technology in Islam is provided by the Banū Mūsā’s *Book of Ingenious Devices*, written about the middle of the 3rd/9th century in Baghdad.¹⁵ Although these three brothers undoubtedly took the works of Philo and Hero as their starting point, their work exhibits a greater mastery of physical media than does that of either of their predecessors. In

15 *The Book of Ingenious Devices* has been published in both English and Arabic: the Arabic edition is edited by Aḥmad Y. al-Ḥasan, Institute for the History of Arabic Science, University of Aleppo, 1981; the annotated English translation is by Donald R. Hill, Reidel, Dordrecht, 1979.

particular they display an astonishing skill in the manipulation of small variations in aerostatic and hydrostatic pressures. They also made considerable use of automatically-operated conical valves in control systems, and were the first of a succession of Arabic engineers to demonstrate a pre-occupation with 'in-line' automatic controls. In many ways they were ahead of their time, and none of their successors attempted to improve upon their results, although their work was well known and appreciated in the Muslim world. Perhaps the words of Ibn Khaldūn explain why no advance was made again before the introduction of pneumatic instrumentation in modern times: 'there exists a book on mechanics that mentions every astonishing remarkable and nice mechanical contrivance. It is often difficult to understand, because the geometrical proofs occurring in it are difficult. People have copies of it. They ascribe it to the Banū Shākīr'.¹⁶ There is nothing of direct relevance to our present theme in the Banū Mūsā's book, no addition to our collection of clockwork elements. Their importance in the present context is nevertheless great, because they exemplify a recurring characteristic of Arabic engineers — a pre-occupation with finding means for controlling the release of energy. And uncontrolled energy is both useless and dangerous.

We now have to make an apparent digression, and consider a chapter called *Wheels which turn by themselves*, which is to be found in six different Arabic manuscripts.¹⁷ There are variations from one manuscript to another, but there are enough similarities to suggest that they all came from a common source. The devices have often been dismissed as unintelligible or absurd or both, but our written sources are not so abundant that we can afford to dispense with any document, however fanciful it may seem. Two devices, in particular, are worthy of attention.¹⁸ In one of these a large wheel has a number of S-shaped pipes, partially filled with mercury, fixed to one of its sides, in such a manner that when the wheel is at rest in any position it is statically in balance. The wheel is mounted on an axle, which also carries, at either side of the main wheel, a chain-of-pots wheel. According to the text, once the large wheel has been set in motion, it will keep on rotating because of the action of the mercury sliding up and down in the pipes. The second device consists of a pair of water-wheels driven through gears by the descent of two lead weights attached to ropes wound around the main axle of the machine. It is reasonably certain that I have given here the basic principles described in the two passages, although there are obscurities in the text and the accompanying illustrations add little to our understanding. Both concepts are, of course, nonsense — the first because there is no input of energy and the second because the descent of the weights is uncontrolled. It is assumed that this treatise

16 *Muqaddima*, English translation by F. Rosenthal, Routledge and Kegan Paul, 2nd ed. (London, 1967), vol. 3, p. 132.

17 See Thorkild Schioler, *Roman and Islamic Water-Lifting Wheels* (Odense University Press, 1973), pp. 72-8.

18 Folios 6R to 8R in MS 954 of the Bodleian Library, Oxford.

was written for the amusement of courtly circles and not for practical application, but nevertheless it is difficult to understand why it was written at all. We can conjecture that the writer knew quite well what he was about and that he omitted certain essential components in order to safeguard 'trade secrets'. Weight is lent to this supposition by the existence of a practical machine which combines the main principles of both machines — mercury escapement and weight-drive.

The *Libros del Saber* were prepared in Spain in A.D. 1277 under the direction of Alfonso X of Castile, with the express purpose of making Arabic knowledge available in Castilian.¹⁹ It consists of translations and paraphrases of Arabic works some with known authors some anonymous. In the latter category come the five clocks described in the last section of the work, only one of which concerns us for the moment. This consisted of a large drum made of walnut or jujube wood tightly assembled and sealed with wax or resin. The interior of the drum was divided into twelve compartments, with small holes between the compartments through which mercury flowed. Enough mercury was enclosed to fill just half the compartments. The drum was mounted on the same axle as a large wheel powered by a weightdrive wound around the wheel. Also on the axle was a pinion with six teeth that meshed with 36 oaken teeth on the rim of an astrolabe dial. The mercury drum and pinion made a complete revolution every 4 hours and the astrolabe dial made a complete revolution in 24 hours.

This type of timepiece had been known in Islam since the eleventh century — at least 200 years before the first appearance of weightdriven clocks in the West. The *Libros del Saber* was translated into Italian in 1341, but it was not until 1598 that a similar clock was described in a treatise by Attilio Parisio. It seems likely, although it remains to be proved, that Parisio's clock was derived from the one in the *Libros*.

A few years later, Solomon de Caus, a German specialist in water mechanisms (1576- c.1635) described a compartmented cylinder clock that was to be the prototype of many examples constructed in exactly the same form which were to appear again and again in the seventeenth and eighteenth centuries.²⁰ Clearly, the compartmented drum, whether filled with mercury or with water, was an effective escapement for weightdriven clocks.

In our search for the precursors of the mechanical clock, no single piece of evidence is more important than an Arabic treatise written in Muslim Spain in the 5th/11th century by a certain al-Murādī. Unfortunately, the only known manuscript copy is so badly defaced that it is impossible to deduce from it precisely how any of the machines was constructed, but enough remains for us to make an assessment of its value. Most of the devices were water-clocks, but the five automata machines are of greater relevance to our subject. The water-clocks, although they are not

19 Ed. Rico y Sinobas (5 vols. Madrid, 1963).

20 Silvio A. Bedini, "The Compartmented Cylindrical Clepsydra," *Technology and Culture*, 3 (1963), pp. 114-41.

without points of interest, do not show any essential advances upon the clock described in the 'Archimedes' treatise. The automata machines are similar to clocks without precise timing, in that the machinery causes events to take place at intervals, such as the opening and closing of doors, the discharging of balls and the movement of figures — in other words actions that we have already encountered in Hellenistic water-clocks. Al-Murāḍī's devices are exceptional, however, on several counts, not the least of which is their sheer size: they contain gear-wheels up to about 70 cm in diameter, counterweights of over 3 kg, and ropes rather than cords or wires are used in the transmission systems. The transmission also includes complex gear trains with segmental gears and epicycles. In one of the devices, for example, the main central gear-wheel had 64 teeth on half its perimeter and meshed with two outer cogwheels, each of which had 32 teeth around its complete perimeter. None of the descriptions of the gearing is complete, but taking the surviving text with the illustrations, there seems little reason to doubt that the machines contained epicycle gears. So here, for the first time we have the transmission of high torque by complex gears, which were far more sophisticated than anything known in Europe before the fourteenth century.²¹ It is also worthy of note that these five machines were powered by water-wheels, the same method that was used in the clock of Su Sung, who was roughly a contemporary of al-Murāḍī. It is therefore just as likely that the Chinese clock was inspired by Islamic ideas as that transmission was in the reverse direction. For our purposes, however, the gears are the most important feature of al-Murāḍī's machines.

Some well-known Arabic scientists built water-clocks, but these cannot detain us for long, because they did not incorporate any of the mechanisms that we are interested in. Al-Khazīnī tells us that the famous Egyptian scientist Ibn al-Haytham (d. 430/1039) built a water-clock, but gives us no details of its construction.²² In about 442/1050 the astronomer al-Zarqāll constructed a large water-clock on the banks of the Tagus at Toledo in Spain.²³ This not only told the hours of the day and the night, but also recorded the phases of the moon. It consisted of two large basins, in a building, fed by underground conduits. As soon as the new moon appeared the basins began to fill, at the rate of one fourteenth of their capacity every day. When the moon began to wane the basins emptied at the same rate, until on the twenty-ninth day both were empty. There was some kind of compensating mechanism, so that if any water were extracted from or poured into one of the basins, the water immediately returned to its correct level. This clock was still in operation when the Christians occupied Toledo in 1085 and one of the clepsydras continued in service until after 1133. The methods of control were

21 Hill, *Arabic Water-clocks*, pp. 36-46.

22 Al-Khazīnī, *Kitāb Mizān al-Ḥikma*, ed. Ḥashim al-Nadwa (Hyderabad, Dn, 1940), 8th Treatise, pt. 1.

23 J. M. Millas Vallicrosa, *Estudios sobre Azarquiel* (Madrid, 1950), pp. 6-9.

probably hydraulic: compensating systems occur in some of the Banū Mūsā's devices, and al-Jazārī, in his fountains, uses various methods for changing the flow from one channel to another. Al-Khāzīnī himself made steelyard clepsydras which are remarkable for the close attention paid to accuracy of results rather than for mechanical ingenuity.²⁴

It has already been noted that the tradition for building water-clocks continued without a break in Syria from the days of the Byzantines into Umayyad times. It seems likely that one of the places where a clock had traditionally been located was by the Jayrūn gate in Damascus: writing late in the 4th/10th century, al-Muqaddasī refers to the 'Gate of the Hours' in a portico by the Jayrūn Gate,²⁵ and it was here that Muḥammad al-Sā'atī built a monumental water-clock about 555/1160. The clock was described by Muḥammad's son, Ridwān, in a treatise written in 600/1203.²⁶ It was based upon the 'Archimedes' water machinery and contained some interesting mechanical elements, together with some inaccuracies and structural weaknesses. A similar clock, but much improved in its engineering, is described in al-Jazārī's great machine book, composed in Diyār Bakr in 602/1206.²⁷ This book is one of the most important engineering documents to have come down to us from any cultural area before modern times, not only for the importance of the fifty machines described in it, but also because the construction of each machine is described with scrupulous care with the avowed (and successful) purpose of enabling later craftsmen to reconstruct any of the machines. There is a wealth of information about techniques and components, many of which were not to appear in Europe until the Renaissance, or even later. Many of these are of great significance in the history of machine technology, including calibration techniques, methods of casting metals, cranks, pumps, control systems, etc. Restricting ourselves, however, to the subject of this paper we should first of all mention a most ingenious water-clock, driven by a submersible bowl called a *ṭarjahār*. This clock, which had a large number of automata, operated on a closed-loop system whereby it continued to work as long as balls were loaded into a magazine at the top of the clock – there was no need to refill the reservoir at the end of the day. Furthermore, as in the small mechanical clocks introduced in the fifteenth century, a large number of interrelated mechanisms were fitted into a confined space, in this case a metal box about 24 cm square in plan by 30 cm high. (Category I, Ch. 4).

24 Al-Khāzīnī, 8th Treatise.

25 Al-Muqaddasī, *Aḥsān al-Taqāsīm*, ed. M.J. de Goeje (Leiden: Brill, 1906), p. 158.

26 Hill, *Arabic Water-clocks*, pp. 69-88.

27 *A Compendium on the Theory and Practice of the Mechanical Arts*, ed. Aḥmad Y. al-Ḥasan (Institute for the History of Arabic Science, University of Aleppo, 1979); annotated English translation, *The Book of Knowledge of Ingenious Mechanical Devices*, Donald R. Hill (Dordrecht, Reidel, 1974).

The first clock, which is a most impressive piece of engineering, was reconstructed full-size for the Science Museum, London as part of the 1976 World of Islam Festival: it worked perfectly. At the top of the clock is a Zodiac circle about one metre in diameter made from sheet copper. The outer rim is divided into twelve equal segments for the signs of the Zodiac, and inside this are two movable annuli, set eccentrically to the centre of rotation of the circle. The outer annulus carries a roundel of yellow glass to represent the sun and the inner one has a roundel of white glass for the moon. Every day the 'sun' and the 'moon' are set to their correct positions in the Zodiac for that day. At daybreak the sun rises above an artificial horizon and the circle turns at constant speed, one Zodiacal signs rising while another sets, until sunset. In the water machinery of the clock there is a sophisticated flow regulator which varies the working period of the clock from day to day according to the length of the hours of daylight for each day (Category I, Ch. 1).

In his introduction to the section on musical automata (Category IV, Ch. 7), al-Jazari mentions an old machine that he had examined. This was driven by a water-wheel and he comments: 'even if the wheel caused a number of rods to fall in succession it would not be slow enough to display the changes adequately'. This is a clear indication that al-Jazari knew about escapement systems for wheels. It is also evidence that al-Muradi's use of water-wheels in automata machines was not unique. Segmental gears, another of al-Muradi's ideas, recur in two of al-Jazari's water-raising machines (Category V, Chs. 1 and 2).

We should now turn briefly to touch upon the subject of the construction of astronomical instruments in Islam. The great scientist al-Biruni (d. after 442/1050) has left us a short treatise on the construction of a geared calendar. This is not so complex as the Antikythera instrument, although Muslim skills in astronomy and metalwork would certainly have been equal to the construction of such a calendar. Al-Biruni's instrument was probably 'made to order' and included only the displays required by his client. It had seven gear-wheels of various sizes and its output comprised the phase of the moon for a given day, together with the positions of the sun and the moon in the Zodiac on that day.²⁸

Al-Biruni says that the wheels on his calendar are like those fitted to the backs of astrolabes. Geared astrolabes have survived in a very few cases, but the survivors are later than the time of al-Biruni. His remark, however, assures us that they were in use before his time. The normal planispheric astrolabe, which is both a computational and an observational instrument, originated in Hellenistic Egypt but its construction and applications were perfected in the Islamic world. Another type of astronomical instrument, the equatorium, was first developed in Muslim Spain early in the 5th/11th century. It is essentially a computational instrument for obtaining astronomical results without recourse to laborious calculations. The

28 Donald R. Hill, "Al-Biruni's Mechanical Calendar," *Annals of Science*, 42 (1985), pp. 139-63.